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ACOUSTIC SCALING:
a review of progress to date, and of possible future development

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Summary

During the past decade, the techniques of acoustic modelling have been developed at Research Department to a degree which enables a realistic subjective assessment to be made of at least the major features of a music studio.

In this report, the successes of the work are reviewed, its limitations are discussed, and consideration is given to the ways in which advancing technology might enable some of these limitations to be overcome in the future.

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1. Introduction

A programme of experimental investigations into acoustic modelling was initiated at Research Department in 1968, and the work has continued at intervals ever since. Detailed results have been published in a series of reports[1-11] ; the purpose of this report is to present a retrospective view, and to consider the directions that possible future work should take.

By comparison with most other scientific disciplines, the study of building acoustics is in a very primitive state of development. Whilst it is possible to specify a number of measurable parameters describing, say, a concert hall, [9,12] these can provide no more than a starting point in its acoustic design; such a specification, even when supplemented by a lifetime's experience on the part of the architect, by no means guarantees that the building will win the acclaim of performers and public. In other words, the final assessment of any acoustic must be made subjectively, and a scale model will provide only a very limited amount of useful information unless it incorporates some means of subjective evaluation.

To pursue this subjective approach, it was therefore necessary to develop loudspeakers of suitably scaled size and frequency range, and of adequate quality to enable recorded music to be played via the model in such a way that it could be assessed by panels of specialist listeners. The development of these transducers, the arrangement of numerous listening tests, and the analysis of results together involved more work than the development of the model itself.

2. Factors determining size of model

2.1. The scaling process

An acoustic scale model, like any other, is derived simply by dividing the linear dimensions of the real structure by a scale factor K. In order that the acoustic properties remain as far as possible invariant under this transformation, several requirements must be met[1] :

(a) The wavelengths of sound must be scaled by the factor 1/K to preserve their relationship to structural dimensions. As the speed of sound in air is substantially independent of frequency, this means simply that all frequencies must be increased by the factor K.

(b) The time for sound energy to traverse a given path is reduced in the model to 1/K of its real value. The time scale in the model is therefore compressed by K:1.

Conditions (a) and (b) may be satisfied by playing and recording audio signals via the model and its transducers at K times normal speed. The transducers and recording equipment must preserve adequate signal quality at scaled frequencies to permit subsequent subjective evaluation at normal replay speed.

(c) Because path lengths in the model are reduced by 1/K, the absorption coefficient of the air should be increased to K times its normal value if the acoustic of a large enclosure is to be realistically modelled. In fact the absorption coefficient of dry air increases with frequency in such a way that air absorption scales accurately, but a reaction between oxygen and water vapour causes excessive high-frequency absorption in moist air.[13] This problem may be overcome either by drying the air in the model, or by using nitrogen instead.

(d) The acoustic impedances and absorption coefficients of surfaces in the model must be the same (allowing for frequency scaling) as in the real structure.

2.2. Practical choice of scale factor

In practice, a very large model is expensive to build or to modify, whereas a very small one presents difficulties in instrumentation because of the very high frequencies involved in its use. The usual compromise is to adopt a scale factor of 8 or 10; all of the BBC's work has been based upon a scale factor of 8.

3. Brief history of modelling work at Research Department

3.1. Background

Until recently the BBC's largest orchestral music studio was Maida Vale Studio 1 (MV1), the home of the BBC Symphony Orchestra. Built originally as an ice rink, this studio has a rather low roof (Fig. 1), a feature that has been commonly held to blame for various acoustic deficiencies. Chief amongst these was the hard or 'wiry' nature of the string tone when a full orchestra was present.

During the mid 1960s, when the studio was due for refurbishment, various possible means of improving the acoustic were considered; these included the very expensive option of raising the roof from about 10 to about 15 metres, without any guarantee of the desired improvement.

An excellent opportunity was thus available to test the modelling technique by attempting to reproduce the acoustic of an existing studio. If this were successful, then the suggested modifications could also be modelled with reasonable confidence in the results. The work would be well repaid if a costly architectural project could thereby be founded on reasonable probability rather than on informed guesswork.

3.2. Early work : the proving experiment

Before the construction of the first model, a considerable amount of preparatory work was needed to design and develop suitable loudspeakers, microphones, amplifiers and recording equipment.[1,4] In addition, a model reverberation room[2] had to be built for measuring the absorption coefficient of all the component parts of the model. The components themselves (for example absorber boxes, carpets, model people) had to be selected or developed to provide acoustic properties corresponding closely to those of their real counterparts.[1,3] After this work, the construction and testing of the model proved to be relatively straightforward.

One of the most important steps in the project was the recording of suitable programme material in anechoic conditions. It is clear that if the acoustic of the model is to be accurately assessed, no reverberant sound must be present in the original programme. A special stereo recording was therfore made in Building Research Station's large free-field room,[10] in which a selection of musical excerpts were played by the English Chamber Orchestra and the Phillip Jones Brass Ensemble*.

A series of recordings was made with the model studio empty (i.e. no musicians), and several studio managers accustomed to working in MV1 were invited to evaluate the results. After acclimatisation to the poor quality of the recordings (the instrumentation was subsequently much improved) they agreed that the acoustic of the real studio when empty had been quite recognisably reproduced. They also pointed out, however that their greatest problem, namely the unpleasant string tone, occurred only in the presence of a large orchestra. Accordingly, acoustic models of seated persons were developed, and the tests were repeated with the model equivalent of a full orchestra. The 'wiry' string tone of MV1 was strikingly reproduced, confirming the validity of the modelling technique to a most encouraging degree.

As a result of this work, much was learned, not only about modelling, but about the presentation of listening tests and the extraction of useful information from the results.[7]

3.3. Modifications to Maida Vale Studio 1

The next step, clearly, was to select and model some of the proposed modifications. These experiments are described in detail elsewhere,[5,6] but two will be briefly recounted here because they illustrate the usefulness of the modelling work.

The first modification made to the model studio was the raising of the roof from 10 to 15 metres (real equivalent). As expected, this increased the equivalent reverberation time by almost half a second to about 2.3 seconds, and additional acoustic treatment had to be installed to restore the original reverberation time. After a series of listening tests, the surprising conclusion was reached that when the reverberation times in the two conditions were the same there was no perceptible change in the sound picked up by a stereo pair of microphones (although the same might clearly not apply to a listener in the actual studio). It appears, therefore, that if the most expensive of the proposed modifications had been carried out in the real studio, the results would probably have been extremely disappointing. The interesting incidental discovery was made that most listeners preferred a longer reverberation time than the 1.9 seconds of MV1, a fact borne in mind during the design of a later studio.

It had been suggested by Harwood[7] that the objectionable string tone was caused by a flutter echo between the end walls of the gallery at the back; this was indeed confirmed by an experiment in which one of these walls was treated with absorbing material. An alternative approach was suggested by Pierre Boulez, then principal conductor of the BBC Symphony Orchestra. It involved removal of the choir seating, and redesign of the orchestral rostra in the form shown in Fig. 2 : both the musicians and the microphones would thereby be moved backwards and away from the region of the flutter echo.

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*Copies of the tape are available for research purposes from the BBC Transcription Recording Unit.

Tests showed that after the addition of some acoustic treatment to the wall behind the orchestra, the new arrangement worked extremely well, indeed resulting in an appreciable improvement of the overall acoustic.

In the real studio, the Boulez rostra were accordingly installed, and the required acoustic treatment added. The effects were close to those predicted by the model, and both musicians and studio managers have expressed satisfaction with the results.

3.4. The new Manchester music studio

When a new music studio was proposed for the BBC centre at Manchester, it was decided to model the design at Research Department, in collaboration with the architect and the acoustic consultants. Restrictions on site area meant that the studio would have to be of an unusual shape, and the guidance obtained from a model would therefore be of more than usual value. The effectiveness of a number of proposed innovations could also be examined before construction began.

The available floor area was adequate to accommodate a full orchestra (without audience); however, to provide sufficient volume, the studio required a very high ratio of height to floor area. The large volume is required to ensure that the reverberation time is not critically dependent upon the number of persons present. Otherwise, for example, if the studio were satisfactory for a symphony orchestra it might be excessively reverberant when occupied only by a string quartet.

Two particular design features that were expected to be of value were the provision on walls and ceiling of irregularly spaced ribs, and the use of 'randomly' distributed acoustic absorber modules. The purpose in both cases was to assist in the spatial diffusion of acoustic energy and so minimise the occurrence of late discrete reflections. A view of the model studio is shown in Fig. 3.

The width of the real studio is about 22m., and its length 27m.; the height was initially envisaged as between 13m. and 15m., to be decided by experiment. Initial listening tests through the model revealed a very pleasing acoustic; further tests in which the roof height was varied showed the same phenomenon as had been observed in the Maida Vale model: namely, that for a constant reverberation time changes in roof height did not perceptibly affect the output of a stereo pair of microphones. A height of 13.7m was finally adopted to provide a reasonable compromise between the volume required to make the reverberation time substantially independent of studio occupancy and on the other hand, the cost of the foundations needed to support a higher Building.

Another result of work on the Maida Vale model had been the preference of listeners for what would previously have been considered a surprisingly long reverberation time. A series of recordings was therefore made through the Manchester Model in which the reverberation time was varied from 1.9 to 2.8 seconds. Listening tests showed a preference among subjects for about 2.25 seconds, which was therefore chosen as the design value for the real studio.

Construction of the Manchester studio is now complete and at the time of writing, final installation work is in progress. Fig. 4 shows a photograph taken in September 1980.

3.5. Behaviour of acoustic absorbers in different environments

One particularly interesting fact emerged from the experiments on the Manchester model: namely, that the measured absorption coefficient of an absorber module depends very considerably upon the volume of the room in which it is measured. The model reverberation room[2] is a scaled version of the ISO standard room, and was used in the measurement and optimisation of the absorber modules designed for the Manchester model. However, it was found that to achieve a given reverberation time in the model studio, the number of absorbers needed was considerably smaller than that calculated: in other words, their absorption coefficient in the studio (of equivalent volume 8100m^3.) appeared to be up to twice that measured in the reverberation room (of equivalent volume 200 m^3.) When the concrete shell of the real studio was completed, measurements were made on a number of absorber modules randomly distributed on the floor, and the apparent increase in absorption coefficient was confirmed. No adequate theoretical explanation of the phenomenon has yet been found, but knowledge of its existence enabled a much more accurate estimate to be made of the amount of acoustic treatment required in the Manchester studio.

4. Instrumentation: Limitations, and possible future improvements.

4.1. Loudspeakers

The development of one-eighth scale loudspeakers[4] was the most difficult single step in the modelling project. In their present form, these loudspeakers possess two significant shortcomings. Firstly, their tonal quality (when transformed down to normal audio frequency) is distinctly inferior to that achievable with full-size studio monitors. As a result, it can be difficult to distinguish the tonal colorations inherent in the speakers from those caused by the studio acoustic. Secondly, the large physical size of these loudspeakers (equivalent height 3.6m. : see Figs.2 and 3) means that the effective source of high-frequency radiation is unrealistically high above the studio floor, and separated by about 1m from the mid-band source.

In the ten years since the development of the model speakers, a number of advances have been made in the design of drive units, and the following improvements could probably be made:

(a) Midrange unit.

The midrange drive unit is an ordinary hard-dome tweeter, and covers the equivalent frequency range of 375Hz. to 2.6kHz. It is in this range that tonal colorations are most clearly audible, so that the tonal quality of the loudspeaker assembly is dominated by this unit. Replacement by a more modern soft-dome tweeter would probably provide a considerable improvement, and would also extend the equivalent bandwidth of the midrange unit down to 250Hz, thereby placing less demand on the tonal quality of the low-frequency unit.

(b) High-frequency units.

As may be seen from the photographs (Figs. 2 and 3) the high-frequency band (in equivalent terms 2.6kHz to 12.5kHz) is radiated from a hemispherical array of 25mm electrostatic units. A single such unit would be excessively directional at the top of the band, and would in any case generate insufficient acoustic power to achieve an adequate signal to noise ratio in the model; the use of an array overcomes both problems at the expense of physical size.

Some recent work on piezoelectric plastics[14] shows that it may be possible to design a single high-frequency dome transducer that would provide both a sufficent power output and a wide enough radiation pattern to replace the present electrostatic array.

The performance of the low-frequency unit is probably adequate, so that replacement of the mid and upper units would enable a new loudspeaker to be designed to provide superior tonal quality and increased acoustic output from a box of scaled size comparable to the larger studio monitors in current BBC use.

4.2. Microphones

Throughout the work so far, all recordings have been made via a spaced pair of nominally omnidirectional condenser microphones. These are too large in diameter (6mm) to be satisfactorily omnidirectional at the highest frequencies; besides which, a much more usual configuration for serious music is a coincident pair of cardioid or figure-of-eight microphones.

At present, no directional microphones are available which would be suitable for model work. It is however possible that a design based on a piezoeletric plastic diaphragm could provide a figure of eight characteristic up to 100kHz. In the shorter term, the provision of loudspeakers with a higher power output could enable the existing microphones to be replaced with 3mm condenser types, which are much more nearly omnidirectional ar 100 kHz; at present, these would not provide adequate signal to noise ratio.

4.3. Recording equipment

Normal analogue tape recorders require a certain amount of maintenance to keep them operating within their specified performance limits, and even a small amount of head fouling or maladjustment can cause audible differences between nominally identical machines. In modelling, the requirement at work at eight times normal speed places exceptional demands on the recording equipment; to ensure complete 'transparency' it would be desirable (and now feasible) to design a digital system based on an instrumentation recorder.

4.4. Modelling accuracy

There is no fundamental limitation in the accuracy with which an auditorium can be modelled : its shell, acoustic treatment, furniture and audience can be scaled very closely indeed. However, great care is needed in checking for unintended mechanisms of sound absorption that can occur in real studios and halls. Past examples of this have included floors, ceilings, and ventilation and service trunking.

Typical studio microphones have not so far been successfully modelled at one-eighth scale, but again there is no reason why advances in transducer design should not presently make this possible.

One aspect of a music studio or concert hall which cannot be accurately modelled is the sound field generated by an orchestra or group of musicians. Many musical instruments, for example violins, are strongly directional, but even using multiple channels and much smaller loudspeakers than are currently available, an accurate representation of an orchestra would scarcely be possible. The stereophonic setup used in the work to date clearly falls far short of realism in this respect, but early recordings made in the real Maida Vale studio with a pair of monitoring loudspeakers and a spaced pair of microphones suggested that at least the primary acoustic characteristics of the studio could be assessed in this way. Subsequent work has confirmed this, but has indicated that the effect of objects placed near the orchestra, such as overhead or side reflectors, is not the same in the model as in a real studio with an orchestra. The availability of smaller loudspeakers would effect a partial solution, but this particular limitation in modelling realism seems unlikely ever to be completely overcome.

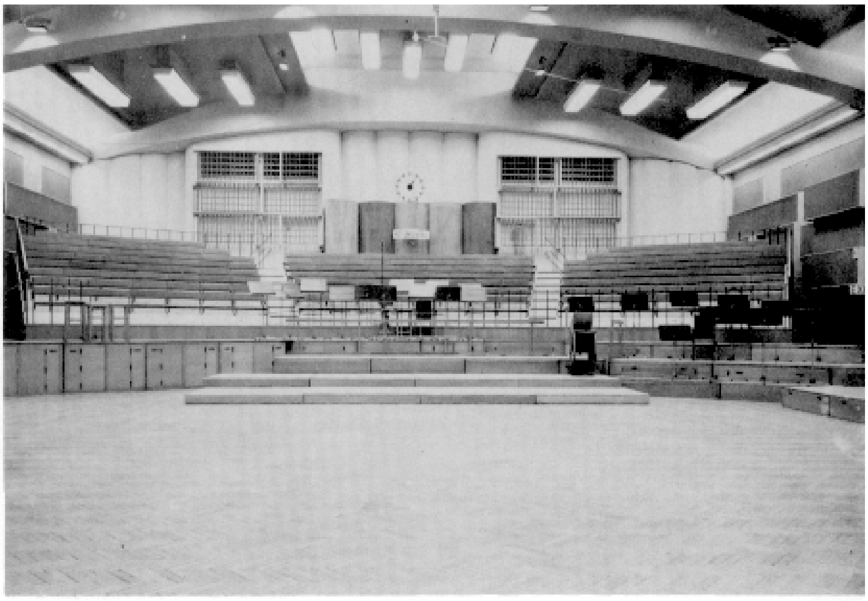

Fig. 1 Maida Vale Studio 1 before modifications

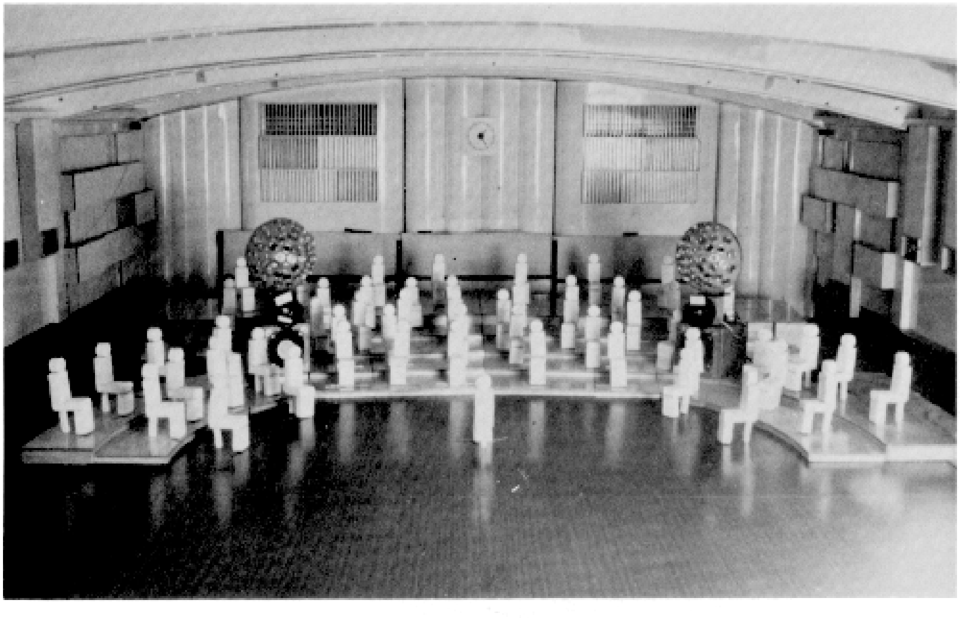

Fig. 2 Model of MV1 with Boulez modifications

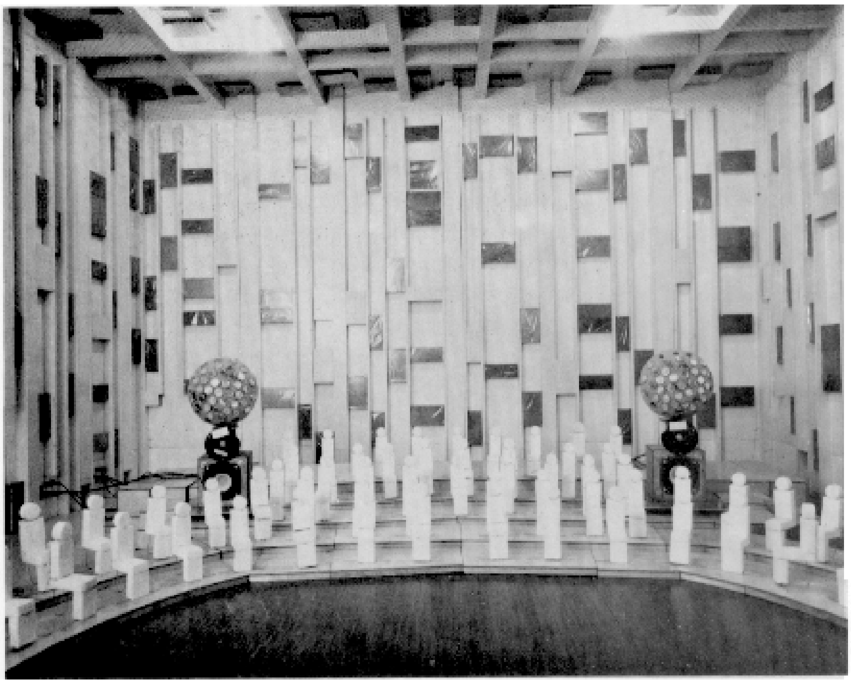

Fig. 3 Model of Manchester Music studio, with loudspeakers and model musicians

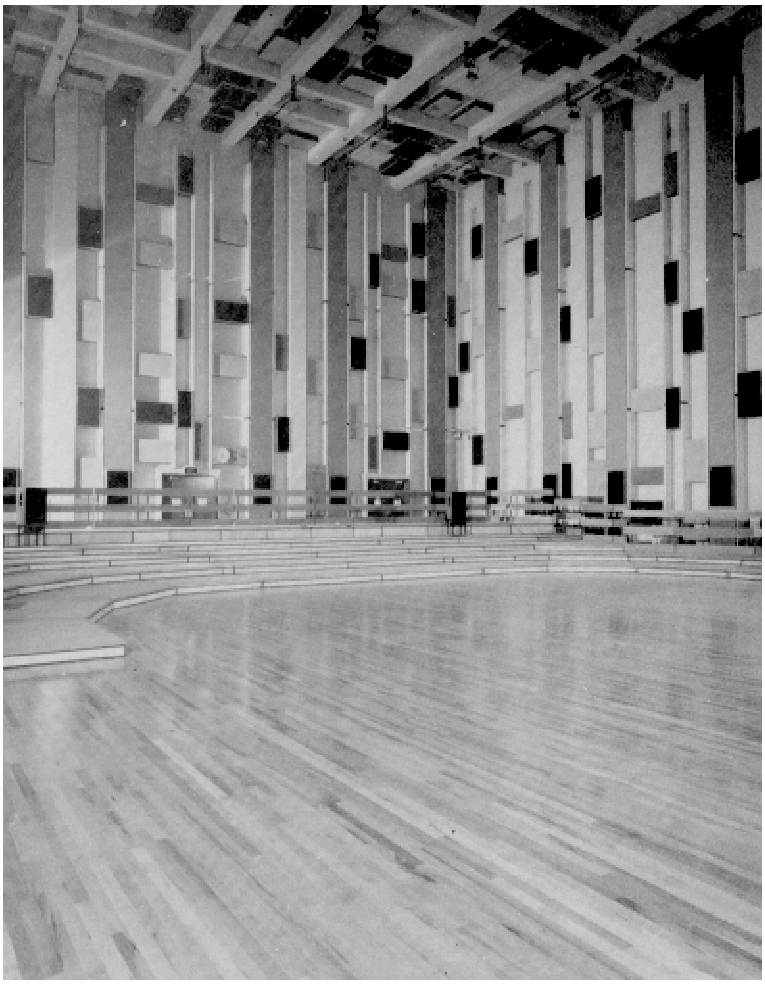

Fig. 4 Manchester music studio, September 1980

5. Conclusions

It has been established that recordings made via a one-eighth scale model of a music studio can provide a very fair subjective impression of the acoustic in the real studio. Prior to the construction or modification of such a studio, the building and testing of a model have proved to be well worthwhile; indeed, for the models described, even the cost of the preliminary research and development has been recouped. In the case of the Maida Vale studio, the very expensive option of raising the roof was abandoned at an early stage, whilst for the Manchester studio, considerable savings were made with regard to the costs of the building foundations and the acoustic treatment.

The loudspeakers, microphones and recording equipment upon which current modelling work is based were designed in about 1970, and in the light of advances made since then, could be considerably improved. This would greatly increase the ease and accuracy of subjective assessments, which (although difficult at best) are made more difficult by the shortcomings of existing instrumentation.

Finally, the limitations of the modelling approach should be borne in mind; chief amongst these is the difficulty of reproducing the sound field of an orchestra. Experience has shown that provided reflecting surfaces are not placed close by, an stereo pair of louspeakers can represent an orchestra quite convincingly.

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